Modelling salinity and concentration polarization in batch reverse-osmosis

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2.290 Final Project

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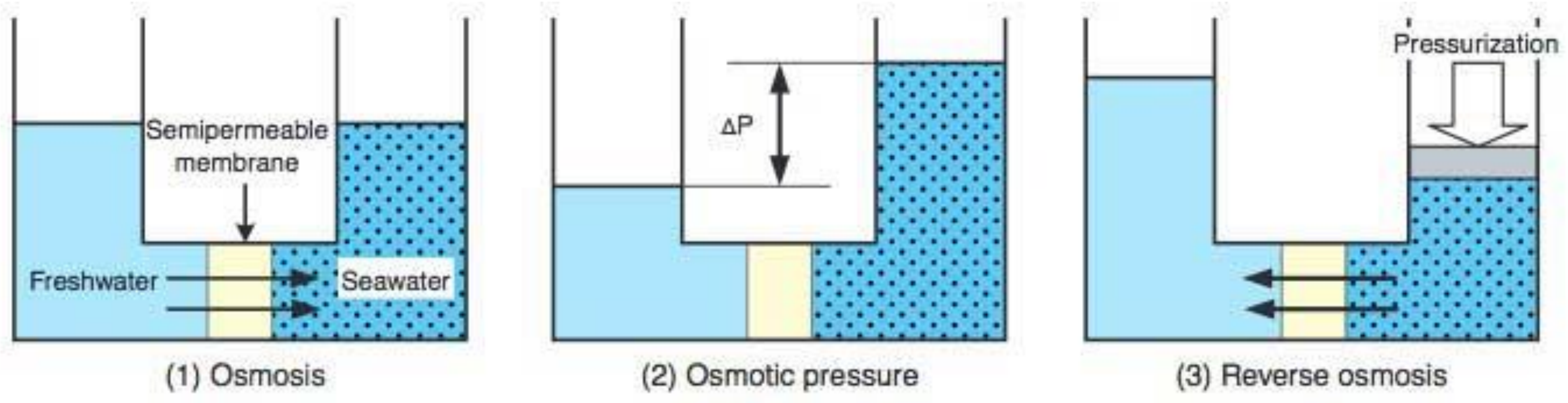
Objective

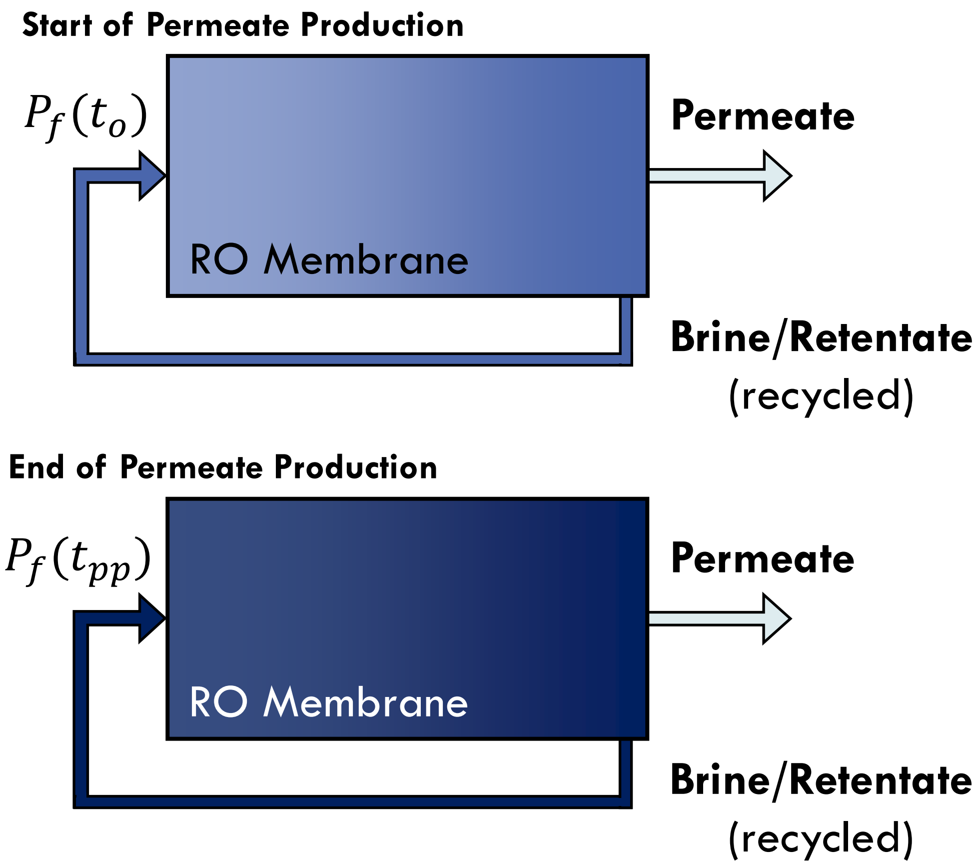
Model feed and permeate salinity in a batch RO system over time and over space

[1]



$$J_w = A(\Delta P - \Delta \pi)$$

Batch reverse-osmosis



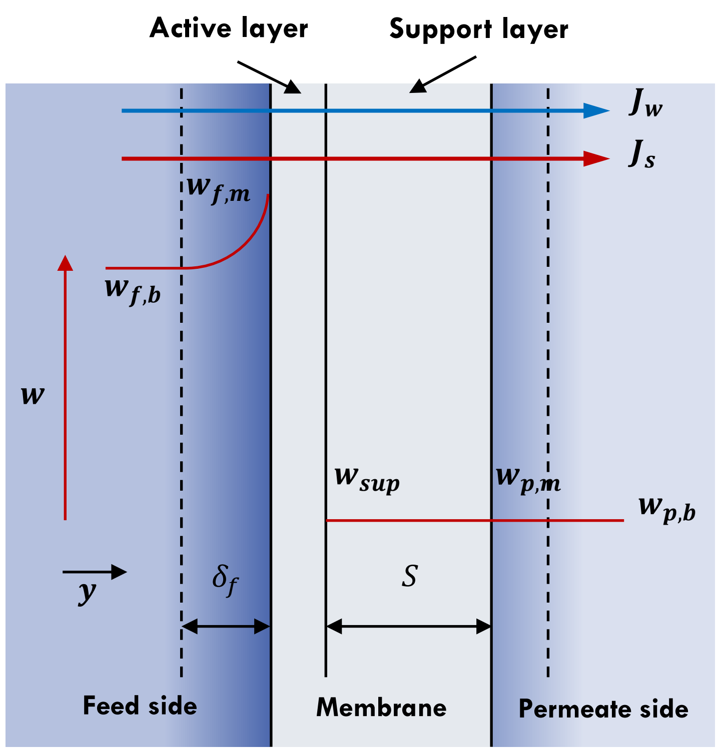
P_f increases from t_0 to t_{pp}

- Brine/retentate is recycled while producing permeate
- Both salt and water permeate membrane
- After permeate production, system must be reset (flush and recharge stage) – no pressurization to feed during reset

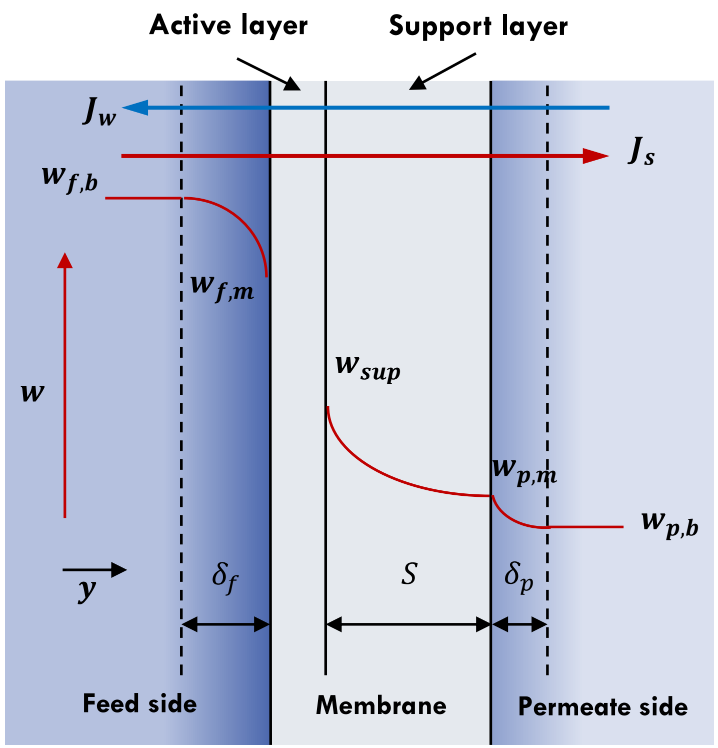
Concentration Polarization

- Build up or dilution of salt due to advection
- Water flux reverses direction during flush/recharge → analogous to forward osmosis

PERMEATE PRODUCTION STAGE



FLUSH/RECHARGE STAGE



Flux and concentration polarization equations

Batch stage

$$J_w = A\left(P_f - \left(\pi_{f,m} - \pi_{p,b}\right)\right)$$

$$J_s = B\left(w_{f,m} - w_{p,b}\right)$$

$$C_{f,m} = CP_f C_{f,b} + \frac{J_s}{J_w}\left(1 - CP_f\right)$$

Flush stage

$$J_w = A\left(P_f - \left(\pi_{f,m} - \pi_{sup}\right)\right)$$

$$J_s = B\left(w_{f,m} - w_{sup}\right)$$

$$C_{f,m} = CP_f C_{f,b} + \frac{J_s}{J_w}\left(1 - CP_f\right)$$

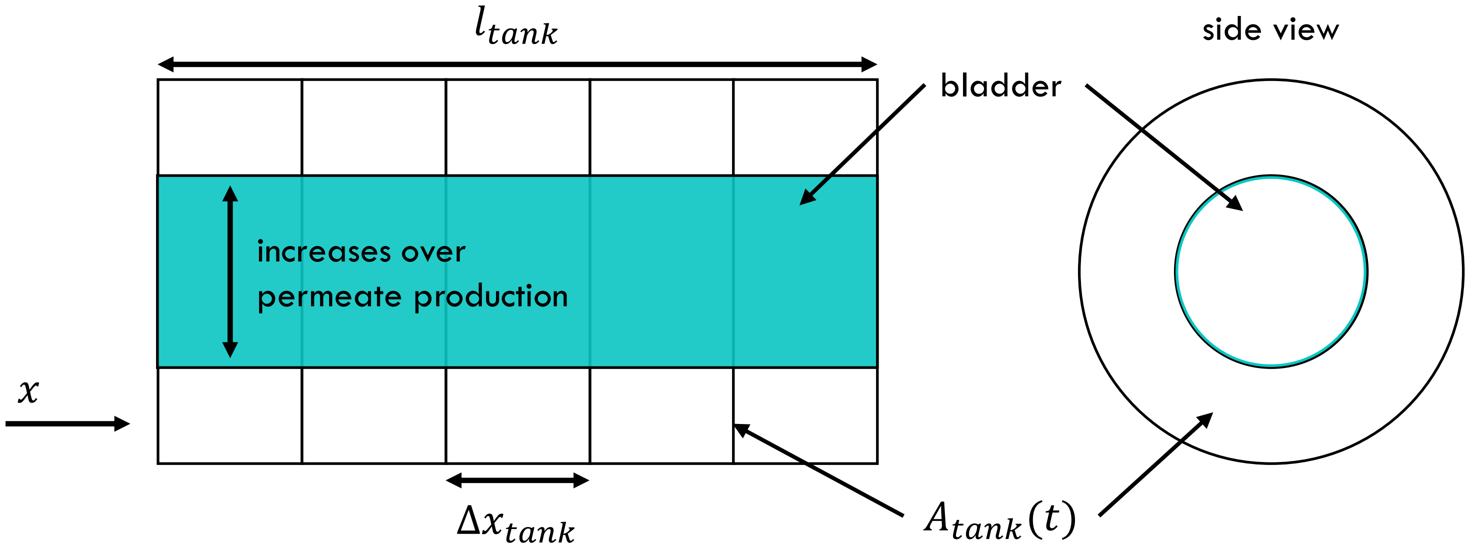
$$C_{p,m} = CP_p C_{p,b} + \frac{J_s}{J_w}\left(1 - CP_p\right)$$

$$C_{sup} = CP_{sup} C_{p,m} + \frac{J_s}{J_w}\left(1 - CP_{sup}\right)$$

System Description – Batch RO

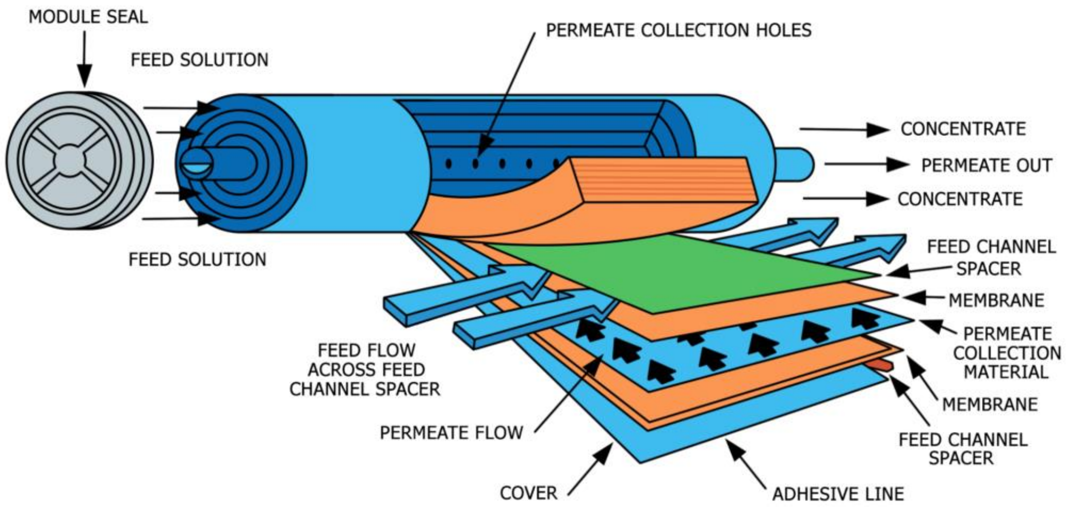
- Tank and spiral-wound membrane module (no piping)
- **Permeate production**: retentate/brine leaves last cell of membrane module, goes through a circulate pump to re-enter tank
- **Flush**: feed enters through circulate pump and then enters tank. Reject leaves through last cell of membrane module

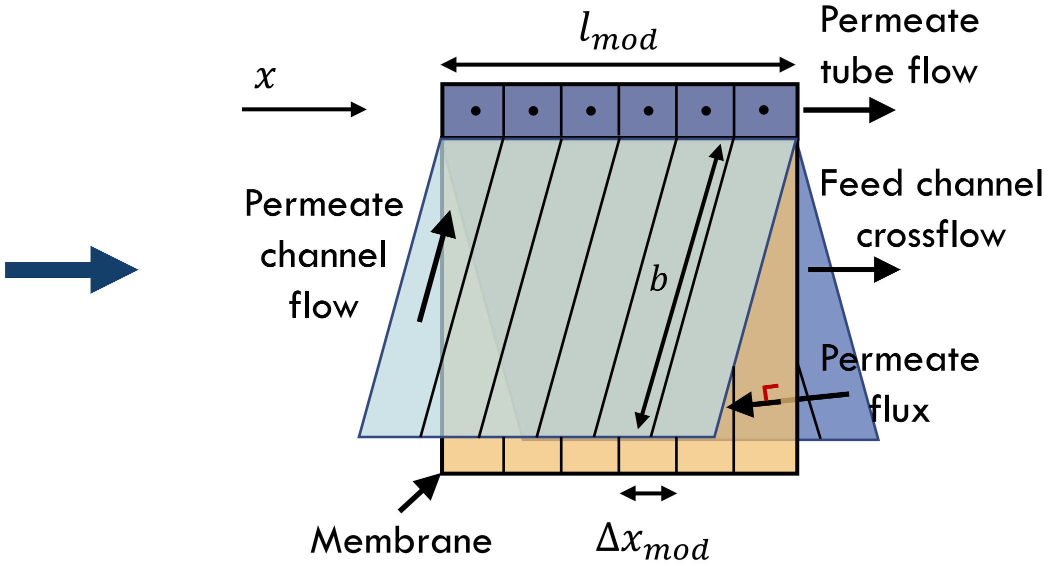
System Description – Tank



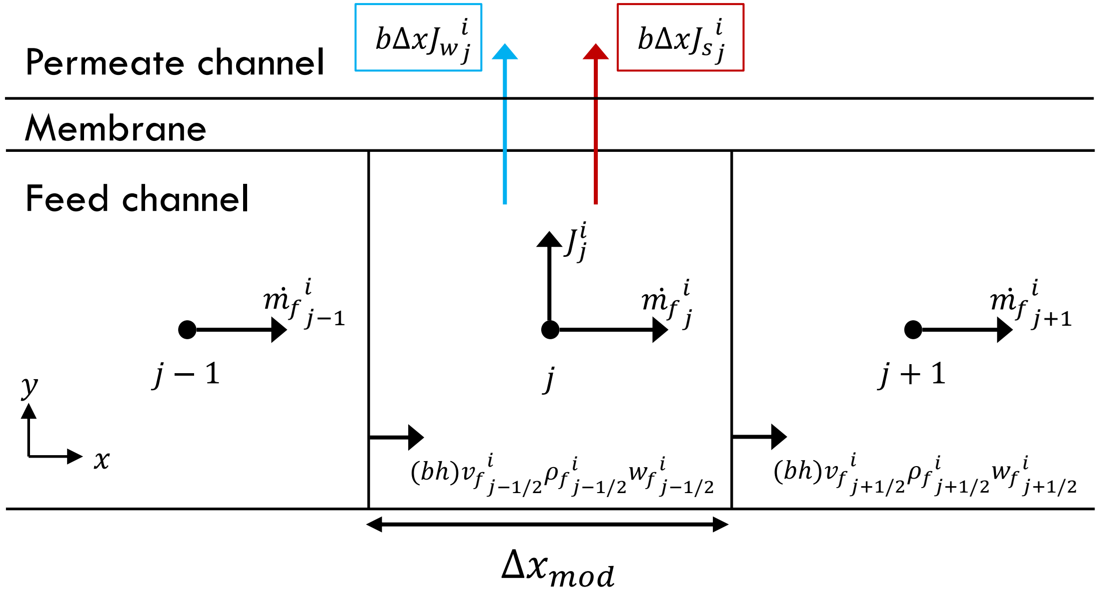
Membrane module – feed channel

[2]





Salt balance – feed channel



$$(\rho w)_j = \frac{[kg\ of\ solution]}{[m^3]} \frac{[g\ of\ salt]}{[kg\ of\ solution]}$$

$$(\rho w)_j = \frac{[g\ of\ salt]}{[m^3]}$$

$$V\frac{d(\rho_f w_f)_j^i}{dt} + (bh)v_{f_{j+1/2}}^i(\rho_f w_f)_{j+1/2}^i - (bh)v_{f_{j-1/2}}^i(\rho_f w_f)_{j-1/2}^i + J_{s_j}^i b\Delta x_{mod} = 0$$

$$(\rho_f w_f)_j^{i+1} = (\rho_f w_f)_j^i + \frac{\Delta t}{bh\Delta x_{mod}}\left(\dot{m}_{f_{j-1/2}}^i\left(\frac{w_{f_{j-1}}^i + w_{f_j}^i}{2}\right) - \dot{m}_{f_{j+1/2}}^i\left(\frac{w_{f_j}^i + w_{f_{j+1}}^i}{2}\right)\right) - \frac{\Delta t}{h}J_{s_j}^i$$

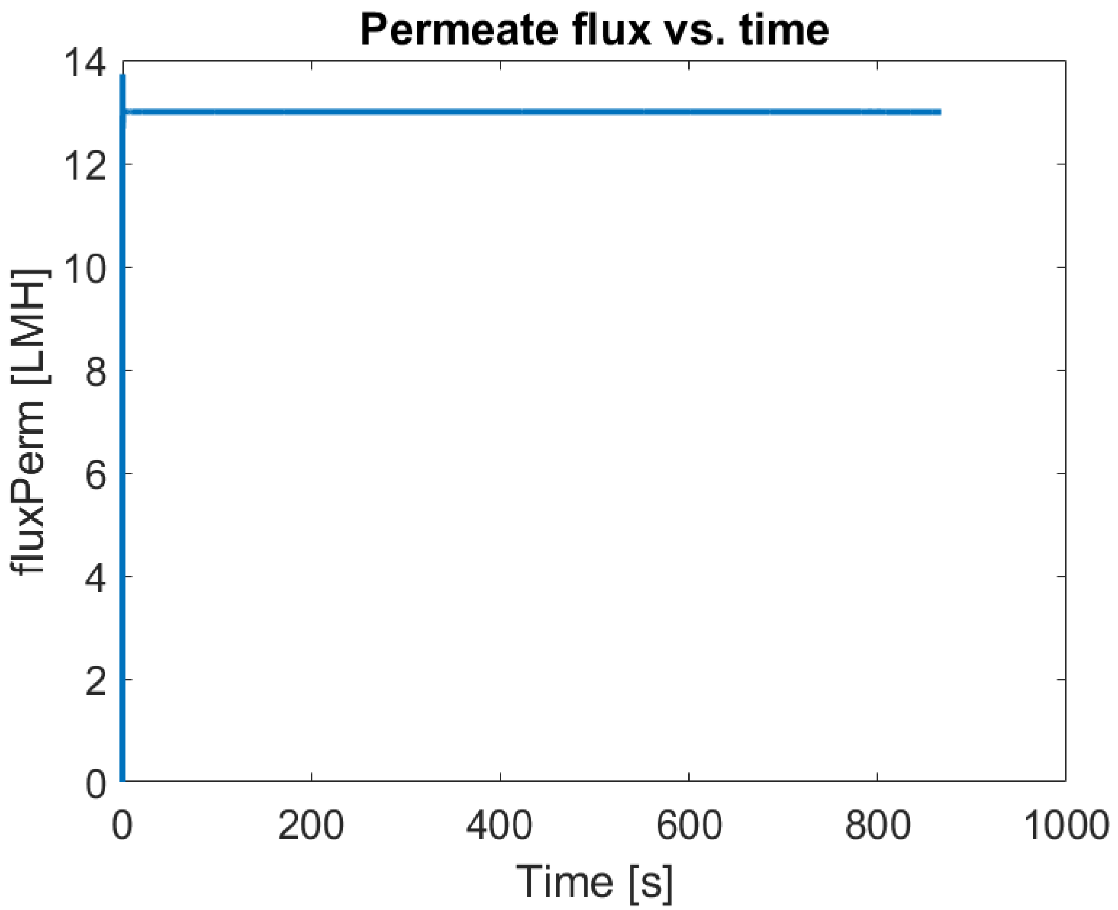
Selection of dx and dt

- Based on dt, minimum area of tank was found to estimate the maximum velocity at any time
- dx > maximum velocity x dt

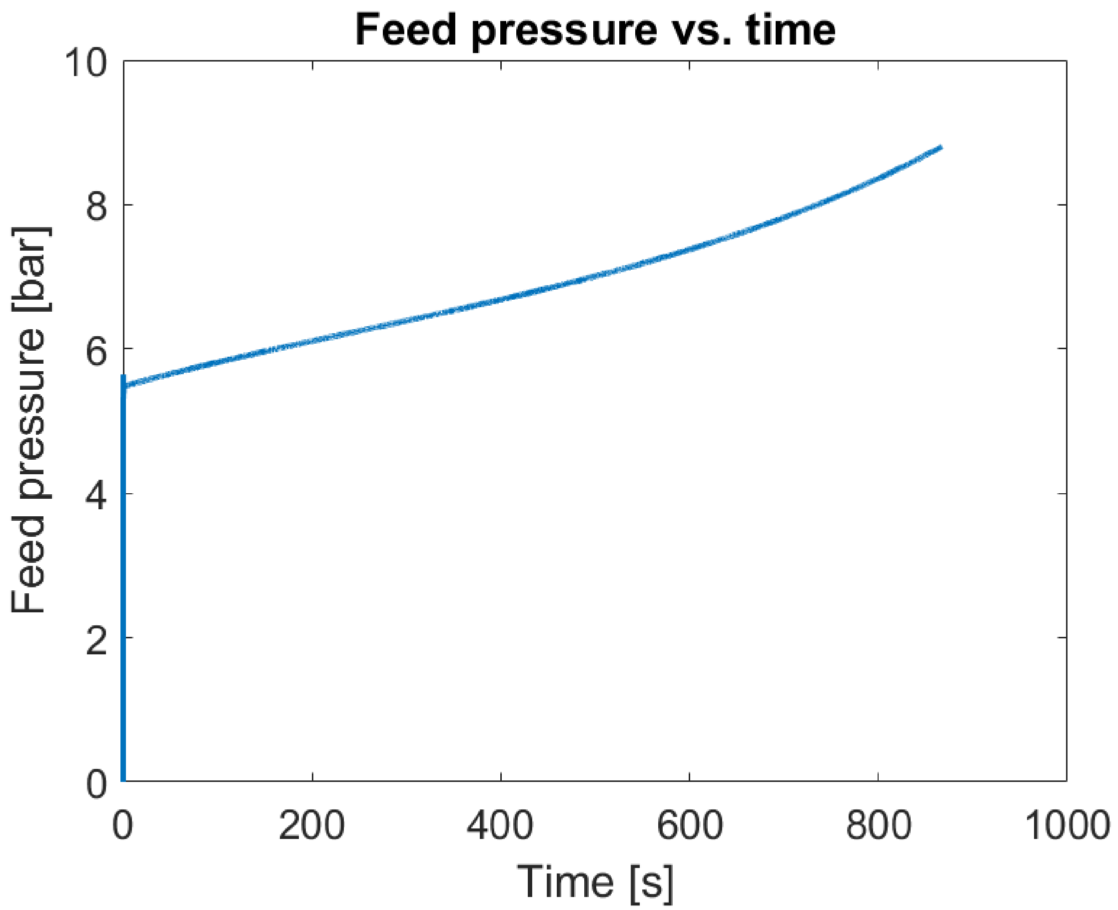
Initial Conditions

- Uniform at starting feed salinity
- Velocity at every cell determined by circulation flow rate
- Water and salt fluxes assumed to be zero
  - Not realistic to assume the salt flux is zero
- No concentration polarization

Results



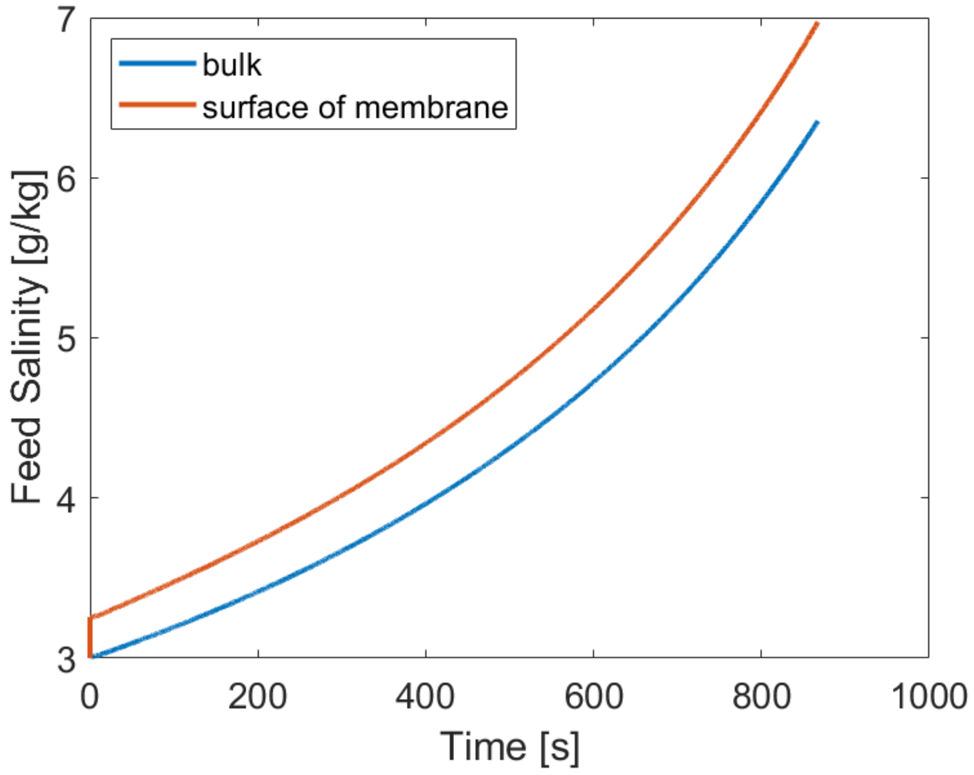
Permeate flux vs. time
fluxPerm [LMH]
0
2
4
6
8
10
12
14
0
200
400
600
800
1000
Time [s]



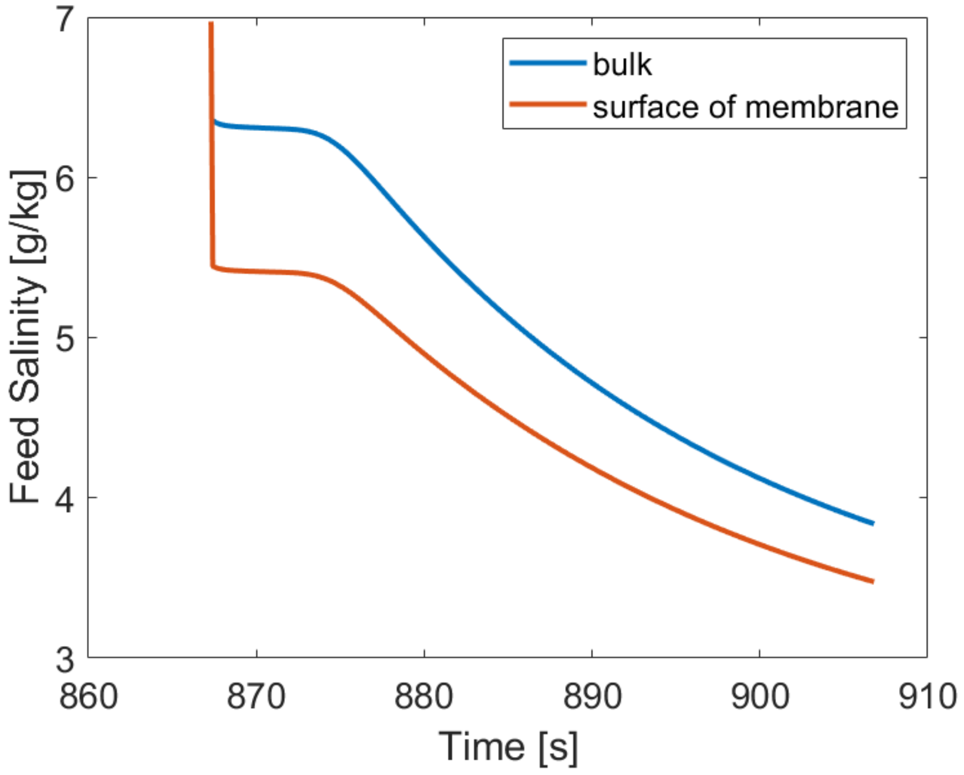
Feed pressure vs. time
Feed pressure [bar]
0
2
4
6
8
10
0
200
400
600
800
1000
Time [s]

Results

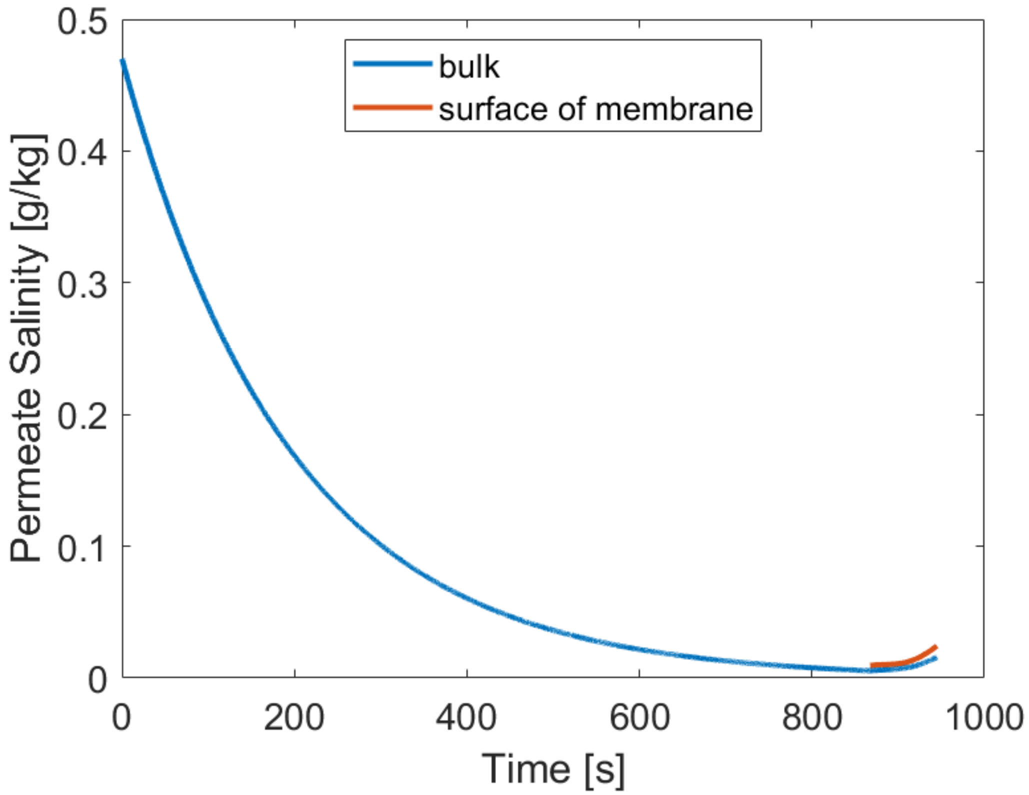
Permeate production



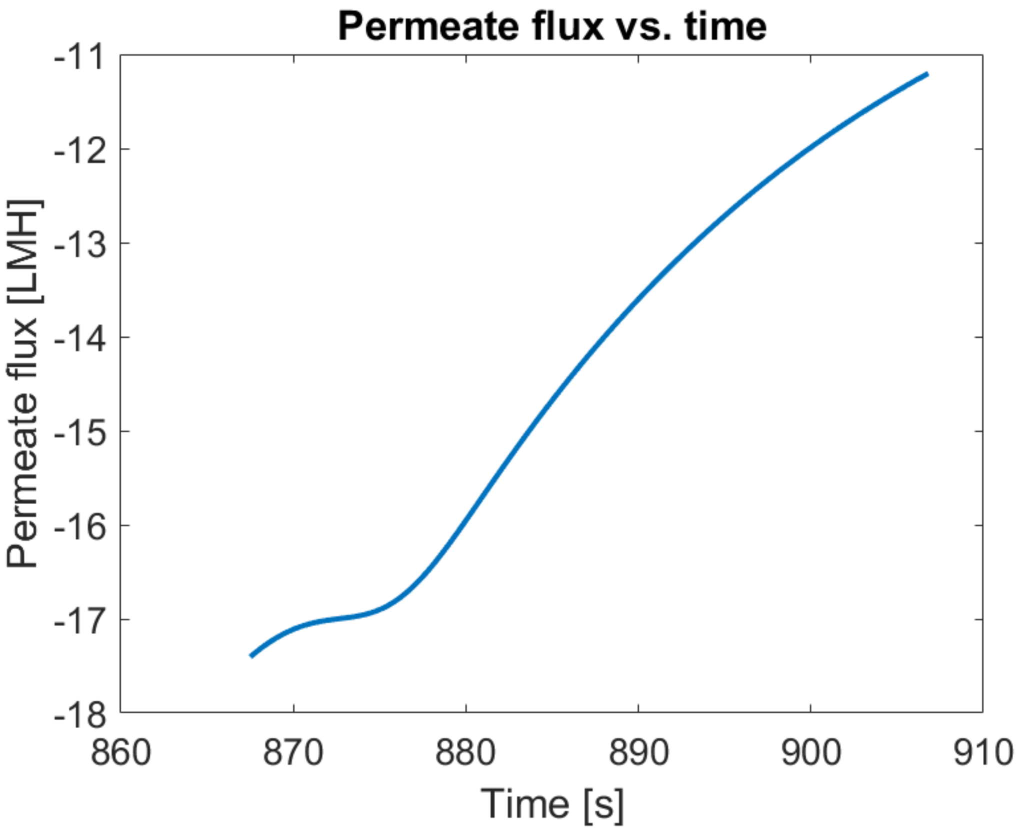
Flush



Results

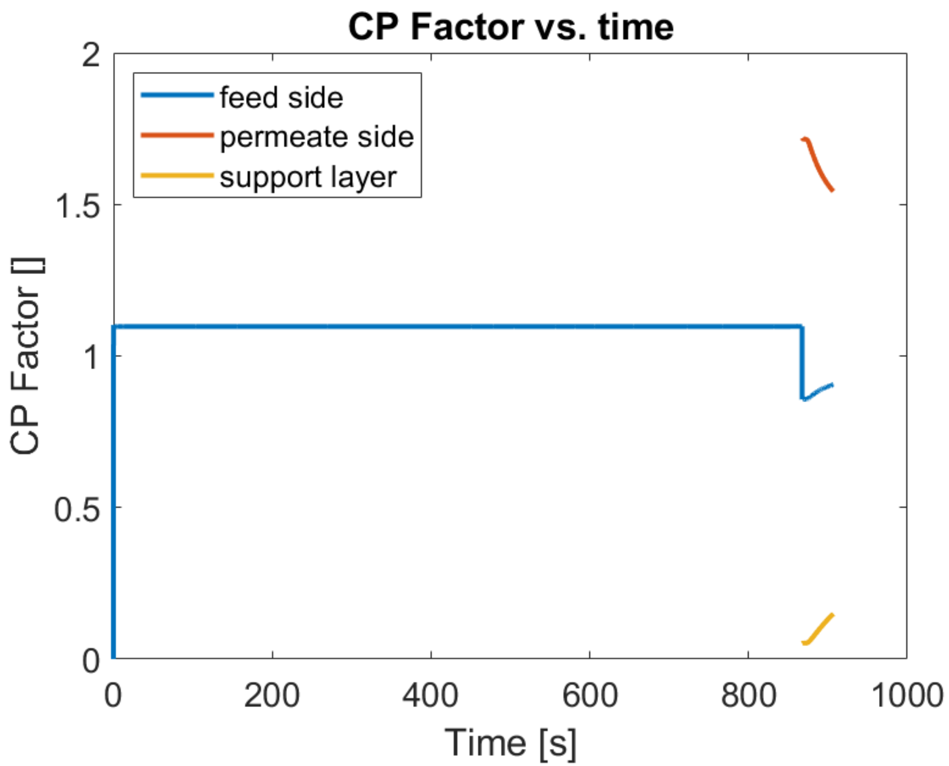


0.5
0.4
0.3
0.2
0.1
0
Permeate Salinity [g/kg]
bulk
surface of membrane
0
200
400
600
800
1000
Time [s]



Permeate flux vs. time
-11
-12
-13
-14
-15
-16
-17
-18
Permeate flux [LMH]
860
870
880
890
900
910
Time [s]

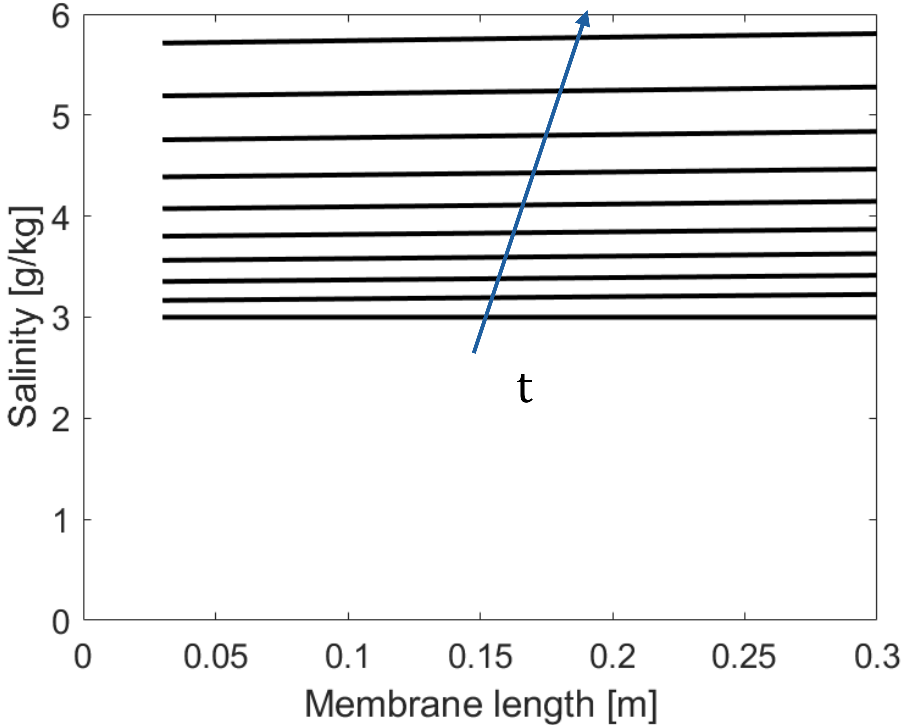
Results - problems



CP factor for support layer should not be less than 1

Salinity along length of membrane module

End of permeate production



Start of permeate production

Should the salinity profile be this linear?

Thank you!

References

[1] https://www.yokogawa.com/sg/library/resources/yokogawa-technical-reports/ecube-aqua-application-portfolio-for-reverse-osmosis-membrane-diagnosis/

[2] https://www.idreco.com/reverse-osmosis/